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NOISES FROM "NOISES OF MODERN AIRCRAFT"
"METHODS OF DIMINISHING THEM"

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INTRODUCTION

1. Preliminary Remarks

Despite the considerable progress made in noise control in aviation, the noise level in modern aircraft is quite high.

Table 1 indicates the ranges of noise intensity for certain types of aircraft as measured in the cockpit (for commercial aircraft, in the passenger compartment).

TABLE 1

NOISE LEVELS OF VARIOUS AIRCRAFT

Type of aircraft	Noise level, db
Fighters with IMA (Instrumentornaya gruppa - engine, propeller unit)	120-130
Medium bombers	110-128
Heavy bombers and passenger aircraft	90-110

There are still quite considerable, even in aircraft of the same type. The noise level in jet aircraft is usually less than in craft with WMS.

The noise level in many aircraft to reach magnitudes such as to make it impossible to converse. At such levels conversation is completely impossible, and prolonged exposure to such noise cause a temporary decrement in hearing. Even the use of special communication instruments (interphones, radios) designated for operation under noisy conditions do not assure that speech will be intelligible. There are lower noise levels at which conversation is possible, but these are exhausting to persons subjected to them for long periods.

Table 2, based on the author's data, adduces levels of typical aircraft noise and the approximate human response thereto (without helmet or sound insulation in the cabin).

TABLE 2

QUALITATIVE EVALUATION OF NOISE INTERFERING WITH ACTIVITY

Noise, db	Subjective evaluation
80	Noticeable noise
90	Noise is disturbing. Voice raised in conversation
100	Noise is irritating
110	Conversation impossible even at top of one's lungs
120	Noise is oppressive and disorienting
130	Feeling of pain.

It goes without saying that the passengers in an aircraft should be able to converse without special effort and not be subject to excitation by noise. This corresponds to a level of approximately 90 to 105 db, although this level exceeds that in well-built trunk-line railway car. Aircraft noise is more "comfortable," as railway noise is "sharper" and more irregular. Thus, in evaluating the reaction to a noise, it is necessary to reckon not only with its intensity, but its pitch harmonics.

In military aircraft the crew workers in helmet-encased headphones, which considerably ease its work. Here, in evaluating permissible noise level, it is necessary to allow for maximum possible impairment of the quality of communication by radio and among crew members. In this situation a noise level of 115 to 120 db represents a maximum at which it is today still possible to have satisfactory communication.

How is noise to be reduced in aircraft?

Of major significance in this respect is reduction of noise at its sources in the aircraft and provision of soundproof cabin walls.

Table 3 shows the possible limits of noise reduction relative to the overall level, f_n , and to that of various frequency bands, $f_{\Delta f}$, with the use of sound insulation and diminution of noise at the source for a twin-engine passenger aircraft.

Table 3 is divided into 2 portions.

The first shows noise levels from major sources with and without attention to possible maximum possibilities of reduction therein and on the assumption that the cabin wall carries no insulation. Thus, for engines of this power, the total propeller noise is 122 db, while use of special low-noise propellers permits the reduction of this factor to 100 to 104 db.

TABLE 3

NOISE IN DB FROM MAJOR SOURCES IN AIRCRAFT, WITH AND WITHOUT CONSIDERATION OF POSSIBILITIES OF REDUCTION THEREIN

Source	Noise level in db from various sources	
	without noise-reduction	with maximum reduction
Propeller	122	100-104
Exhaust	118	100-104
Engine	104	89-99
Ventilation	114	72-76
Vibration of parts	108	74-79
Aerodynamic noise	94	79-84
Total noise level	124	104-108

POSSIBILITIES FOR REDUCTION OF PASSENGER-CABIN NOISE BY INSULATION

Type of Insulation. (cabin wall material)	Total	600-120c	1200-2400c	2400-4800c
No insulation (model with minimum noise level)	105	86	84	82

Type of insulation for cabin	Noise reduction with given insulation, db			
Ordinary aircraft cabin paneling	2-3	2-5	5-7	8-10
Paneling plus insulation, with air space	3-5	3-6	6-9	10-16
Paneling and multi-ply insulation, with air space	3-8	4-10	10-16	20-40

The noise level from ventilation is 114 db. Use of rational ventilation designs and sound insulation of the air ducts makes it possible to reduce noise from this source to 72 to 76 db. With maximum noise reduction in all sources, noise can be brought down to not less than 104 to 107 db in all, i.e., to a level somewhat higher than that from the largest single source of noise with maximum reduction. Under these conditions, the noise from ventilation, vibration of parts, etc., may not exceed 90 to 95 db as further reduction would in any case have no significant effect on total noise level (see below, determination of noise intensity, I_n , and formulas 4 and 4a).

The second part of Table 3 permits evaluation of the effect of various types of cabin soundproofing. Here we examine both the reduction in total cabin noise (105 db being a value selected on the basis of the findings in Table 3, Part 1) and the noise levels in various frequency bands as the effect of soundproofing is felt with particular force at high frequencies.

It is evident that use of the third type of soundproofing permits a reduction of 3 to 8 db in total noise, and of 20 to 40 db in the 2,400 to 4,800 cps band.

Table 3 reveals that the total attainable noise reduction, in db from aircraft noise control and the use of cabin soundproofing, is 25 db, (from 122 to 97 db in maximum noise reduction on and multi-ply soundproofing) and 40 to 50 db in the high frequencies.

In actuality, the total noise level in the aircraft cabin without soundproofing or reduction of noise from individual sources is 124-2, or 122 db, as the cabin walls reduce noise by about 2 db. Assuming that the noise reduction at the source is about 20 db, and the cabin soundproofing is another 5, we obtain a total possible noise reduction of about 25.

This reduction is extremely important to improve intelligibility of conversation in communications lines and for passenger comfort in commercial aircraft.

For aircraft with other noise levels the possible reduction attainable is the same.

In a comparison of Tables 1 and 3 the following questions naturally arise

(1) What are the causes for the high noise levels in aircraft, and how can they be reduced to a minimum?

(2) What noise levels may be considered permissible, considering that the costs of aircraft construction and operation are affected by the weight of the soundproofing they carry and the complexity of the measures used for noise control.

Before proceeding to an examination of these questions, let us discuss the characteristics of the noises of contemporary aircraft and the effect of aircraft noise on the human organism.

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2. Effect of Noise on the Human Organism

Noise irritates the human nervous system and induces changes in the functioning of the apparatus of hearing and speech. In the presence of noise a person involuntarily speaks louder and strains his vocal chords. Sometimes this causes a noticeable change in the pitch composition of speech, a fact that must be considered in planning communications apparatus designed to function in surrounding noise. Long-term presence in noise induces fatigue. Beginning at a particular noise level, and depending upon the pitch composition, one is conscious of a sensation of discomfort, the irritation of the organism by noise increasing very rapidly as the level rises (Table 2). In addition, the irritating properties of sounds differing in frequency are not identical, and the most unpleasant are sounds in the high-frequency portion of the aural band.

Thus, the irritation caused by 400 and 4,800 c is identical if the 440-c noise is 20 db higher. It is therefore essential to devote particular attention to reducing the high-frequency components of noise, thus making it more "comfortable."

It must also be noted that the intelligibility of speech under conditions of noise depends upon the speech components being higher than the noise in the range from 250 to 3,500 to 4,000 c. Therefore, for raising the intelligibility of speech it is desirable to reduce the high-frequency components of noise by all possible means.

All researchers emphasize the importance of taking all possible measures to reduce noise in general, especially noise in the middle frequencies (600 to 4,000 cycles) in particular to assure comfort in an aircraft.

Thus far there are no objective criteria for determining the maximum permissible noise level and the pitch harmonics thereof required to provide the needed standard of comfort. In passenger aircraft the effort is made to reduce noise as far as possible, considering that comfort is assured if passengers sitting next to each other can converse without marked effort.

It has long since been established that noise produces a shift in the audibility threshold due to the masking action of the noise. This is the equivalent of partial temporary deafness, as cessation of the noise produces a gradual return of full hearing.

Figure 15 illustrates the audibility threshold in quiet surroundings for a person of normal hearing (curve 1). It is evident that sounds of varying frequency become audible at various levels of intensity. Curve 4 represents the audibility level of a person with impaired hearing in quiet surroundings.

In the presence of noise the audibility threshold of a normal person changes as per curve 5; curve 2 provides the threshold of the feeling of pain. Thus, in the quiet a person hears all sounds, the intensity of which are higher than curve 1, while in the noise he hears only those levels, whose intensity are higher than curve 5 (the curves adduced pertaining to the pure sound only).

The levels of sound producing a shift in the threshold within the limits of curve 2 produce a feeling of pain. Thus it is clear that noise has a deafening effect which contributes to poor comprehensibility of speech listened to in noisy surroundings.

The curves for shift in audibility level -- audiograms -- are usually plotted on the audibility level in the quiet. Thus, in the absence of noise an audiogram will take the form of a straight line coinciding with the horizontal axis. Consequently, in the presence of noise the audiogram becomes elevated, remaining stable when the noise characteristic is constant, while after its elimination there is a slow return to the starting position. The after-effect of the noise depends on the duration of the effect of the noise on the ear. After one hour of subjection to 125 db the hearing returns to normal 3 to 4 hours later.

Some researchers assert the existence of an industrial deafness subsequent to long terms of work in aviation, but this cannot be regarded as firmly established.

The shape of the audiogram depends upon the nature of the pitch harmonics. The audiograms of aircraft noise are very similar in shape if they are taken in a single helmet-mounted earphone.

To determine whether the noises of various aircraft affect hearing, the author recorded noise audiograms in several aircraft. Toward this end a special instrument, termed an audiometer, was built; it consisted of a portable RC sound frequency oscillator, with output db attenuator.

The method of measurement was the following. Audiograms of several individuals were taken in a quiet room; this individual audiogram determining, for all practical purposes, the audibility threshold when the given frequency was transmitted by the audiometer telephone. The same operation was then repeated in an aircraft under conditions of noise. Then, assuming that the air pressure in the telephones is

$$p = kU \quad (19)$$

in which U is the voltage in the telephones, we obtain the following audiogram ordinate:

$$M = 20 \log \frac{p_n}{p_t} = 20 \log \frac{U_n}{U_t} \quad (20)$$

in which the subscripts, n and t , represent, respectively, noise and silence.

The expression $M(f)$, in which f is frequency in c, gives us the audiogram we seek.

This method is particularly convenient since it reduces to a minimum errors having to do with conversions, standardization of telephones, etc.

Figure 10 presents a noise audiogram for several aircraft with reciprocal results.

Examination and analysis of the data we obtained permits the following fundamental conclusions:

(a) the quantitative nature of all the audiograms is identical, meaning that the effect of the noise of various types of aircraft on the apparatus of hearing is identical;

(b) the quantitative change in the magnitude $M(f)$ is such that it is possible to find a single design parameter for noise in modern aircraft regardless of type, something that has already been done;

(c) changes in noise level make it possible to hold, practically speaking, that the audiogram shifts parallel to itself, ie, that it rises with elevation of noise level and declines as noise level declines;

(d) at the measured noise levels and shifts in audibility threshold, the latter is approximately proportional to the change in the level of intensity of noise, in db.

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III. METHODS OF REDUCING NOISE

1. General Considerations

As indicated above, aircraft noise can attain very high levels and must be reduced to a minimum which is determined separately in each individual instance

What are the desirable methods of reducing noise? At what noise levels is noise control most effective?

It must always be remembered that neither noise suppression at the source (quiet propellers, exhaust manifolds, careful sealing of apertures) nor sound proofing can effect any considerable reduction of cabin noise independent of each other.

Separate performance of any of these measures is meaningful only if an aircraft already in existence has to undergo corrections of defects in design or in soundproofing. For example, cockpit noise in certain aircraft has been reduced by 5 to 6 db by sealing the landing lights and eliminating crevices in the cockpit housing. There are instances in which cockpit noise has been reduced 25 db in the high-frequency components by sealing cracks. An increase in the rigidity of cabin walls close to the propeller tips may also produce a noise reduction of several db.

However, a significant reduction in cabin noise is attainable only by a combination of measures to suppress noise at the source, and by provision of cabin soundproofing, starting at the drawing board. It is absolutely essential that the cabin be "acoustically homogeneous," ie, that virtually identical levels of soundproofing be provided at all components of the cabin surface. Otherwise the effect of sound insulation will be insignificant

It must be remembered that the noise level in the cabin is determined by its weakest link, ie, if good soundproofing has been provided everywhere except, say, at the windows, cabin noise will be high.

Any cracks and apertures, however insignificant, can markedly reduce soundproofing. However, good soundproofing of the cabin, even if acoustically uniform, will not be effective if noise suppression at the source is neglected. To ignore this is wrong both from the engineering and economic standpoints, as in many cases it is simpler to reduce noise at the source than to reduce its penetration into the cabin. In addition, it is economically unprofitable to try to deaden high noise levels, as the effectiveness of soundproofing is considerably higher at low noise levels.

It must be remembered that the lower the level of external noise (the greater the suppression of noise at its sources), the higher the efficiency of a given type of soundproofing, i.e., the weight of the soundproofing is employed more rationally.

In reality the subjective response to sound is determined not by intensity but by loudness, L . The expression $L(\beta)_n$ is markedly nonlinear. The function $\frac{dL(\beta_n)}{d\beta_n} = \varphi(\beta_n)$ is illustrated in Figure 21. Consequently, at various noise levels an identical reduction $\Delta\beta_n$ from a given level of cabin soundproofing produces a different subjective effect.

When $\beta_n \approx 35$ db, the function $\varphi(\beta_n)$ attains a maximum and declines continuously thereafter with increase in β_n .

2. Suppressing Noise at the Source

Let us examine the possibilities for reducing noise at its most important sources.

Propeller

From Figure 7 it is clear that cabin noise due to the propeller may be reduced if the blade velocity, V_0 , is cut down, and the smallest distance from propeller-tip to fuselage be increased. Use of multibladed low-rpm propellers can also reduce noise by several db.

According to Figure 7, an increase in d_0 to more than 30 to 40 cm has very little effect on noise in the cabin (other sources claim the contrary, however, and indicate that d_0 should not be less than 60 cm).

This is a practicable requirement for new aircraft, a statement that cannot be made as far as reduction in propeller speed and number of blades is concerned, as these latter reduced propeller efficiency to some degree and involve some serious technical difficulties (changes in engine gear-ratio, etc). Nevertheless, considering that a well-designed low-noise propeller provides a reduction of up to 20 db with small loss of efficiency, careful study must be given to the question of the use of such propellers in passenger aircraft in which comfort is a consideration.

To reduce cabin propeller noise it is recommended that the freight compartments of the fuselage be planned to be the closest to the propellers, and that the walls at these points be more rigid, avoiding, if possible, hatches and windows therein.

Exhaust

It has been established that individual exhaust stacks produce an incomparably higher noise level than manifolds or, even more so, manifolds with mufflers. Variations in stack design do affect the noise level, but only insignificantly, as is clear from the curves in Figure 22.

Noise has been measured in octave frequency bands under conditions identical but for stack shapes. Curves 1, 2, and 3 pertain to manifolds of various types, while 4, 5, and 6 apply to stacks.

It is clear that no serious noise reduction is to be expected from one or another type of stack. The use of a manifold can, however, yield a marked reduction in exhaust noise (up to 10 to 20 db). Therefore, despite

some loss of power consequent thereon, manifolds are a highly desirable feature of passenger aircraft design.

A considerable fraction of the exhaust noise energy consists of high-frequency components little subject to diffraction and may therefore readily be screened out. It is therefore desirable to place the exhaust outlet below the wing and close to its leading edge.

Experience has demonstrated that the position of exhaust pipes may have a considerable effect on the level of noise harmonics in the cabin, particularly in the frequency range over 300 to 400 c, where the propeller noise component is lower. In measuring noise only on the level of intensity, this phenomenon is unnoticeable, as the value of L_n is little dependent on exhaust. Therefore the final location of exhaust pipes must be checked against the mock-up of an aircraft, with determination of the noise harmonics an absolute requirement.

When 15 to 20 kg mufflers were added to engines, causing a decline of 1 to 1.5% in engine efficiency, the result was a reduction of 6 to 7 db in total noise on one twin-engined aircraft, and, in another model, 3 to 4 db. Obviously, the benefit will be less with high-speed aircraft having high propeller-tip speeds as well, but the above results merit attention, particularly if they are combined with the use of low-noise propellers.

It may be reckoned that at 300 to 800 hp, and a tip speed of about 175 m per second, the noise level of 3-bladed propeller is comparable to that of the motor exhaust without manifold.

Aerodynamic Noise

Aerodynamic noise, due to the flow of air around the aircraft, declines with improvement in streamlining. No special measures can be proposed to deal with this type of noise, but to the degree that that noise is a high-frequency component of noise harmonics, it is attenuated markedly by the cabin walls.

For their elimination many other types of noise require maximum attention. If they cannot be in appropriate mount. This is worthwhile not only for reducing noise. Fixing the vibration of its parts makes an aircraft more comfortable, increases its life and, what is highly important, eliminates the noise of many small, poorly-fastened elements which, in total, may cause considerable noise.

The noise level of jet aircraft depends very much on the position, of the cockpit relative to the engines. If the nozzle of the engine is removed as far as possible from the cabin, the fuselage space between cabin and nozzle is completely filled with equipment and tanks, and the fuselage gives no resonance, cabin noise will be substantially lower than otherwise.

We have already spoken of the importance of removing cracks. Many writers have given clear evidence of the benefits obtained by tightly fitting the landing light, eliminating glazing chinks therein, etc. Secure fastening of all elements of equipment, careful stopping-up of all cracks and holes without exception, and packing of joints, must be an axiom for every designer.

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IV. MEASURING AIRCRAFT NOISE

1. Methods of Measurement

Measurement of noise in an aircraft is necessary for determining the degree to which it is a disturbing factor and to learn how to reduce it.

The disturbing effect of noise is measured by the shift in the threshold of audibility, the degree of unpleasantness of the noise, and by its effect on the intelligibility of speech.

Noise reduction measures can be properly prescribed only if the distribution of noise energy by sound frequency be known.

It is particularly important to note that this distribution or dependence of noise pitch composition levels, $B_n(f)$, upon frequency is determined in its entirety by the criteria of the noise disturbance effect referred to above. In fact the shift in the threshold of audibility (in the noise audiogram) is completely dependent on $B_n(f)$; the intelligibility of speech is also calculated according to $B_n(f)$. Finally the degree of unpleasantness of the noise, determined by subjective methods, is dependent to a considerably greater degree upon $B_n(f)$ than on the total intensity level, β_n . Therefore determination of the $B_n(f)$ characteristic is the proper object of noise measurements. As this expression may be determined only as the result of the processing of a series of measurements, the effort to find some single magnitude for the characterization of noise is fully understandable.

Noise loudness, loudness expressed in units of sound, "confort index," and other datum points have been proposed for this purpose. However these proposals are not justified, as no single standard of valuation can possibly, as a matter of principle, provide for the differences in the perception of various sound "spectra." Even if this single standard of loudness permits comparison of various noise spectra, the comparison itself is useless, as, given identical loudness, different combinations of pitch will produce different shifts in the threshold of audibility, not to speak of the marked effect of the harmonics on speech intelligibility. Therefore efforts to introduce a "confort index," to calculate the loudness of noise, etc, can be useful only if the noises compared are of the same pitch elements. However, when that is the case, equal success may be met in using, as the general characteristic, the intensity level, β_n , as a magnitude most readily capable of measurement.

Comparison of noises of different pitch components is possible only on the basis of the characteristic of the distribution of harmonics, $B_n(f)$. Only these expressions permit correct determination of required cabin soundproofing and the disturbing effect of noise. Therefore, the object of noise measurement in an aircraft must be the determination of $B_n(f)$ by frequency analysis of the sound spectrum. This is done, as we have stated, by octave filters or sound analyzers. Measurement of the total intensity level must be on the basis of the measurement of the spectrum and is therefore of secondary importance.

The major problem in obtaining β_n is verifying the accuracy of the entire cycle of measurements, as the expression $B_n(f)$ permits calculation of the magnitude β_n (see formulas 2 and 3), and comparison thereof with experimental results. If the magnitudes β_n calc. and β_n exper. differ

only insignificantly the measurements have been performed properly. Otherwise it is necessary to seek the reason for the significant difference. Agreement to within 1.5 or 2 db may be deemed satisfactory.

In view of the inhomogeneity of the sound field in a cabin measurements are taken in the seats both of crew and passengers, the recording microphone being placed at head level and 20 cm from the cabin window or wall. The test is made under conditions corresponding to normal operation, the engine rpm being kept constant to within 50 rpm, at the prescribed speed for this type of operation in horizontal, level flight. This is particularly important for high-speed aircraft, as practice has shown that on change from one to another flight regime, the speed of the aircraft stabilizes at the desired level rather slowly, so that the plane must be given a chance to get into this pattern before the noise measurement is made.

The researcher must make sure that the microphone is not washed by a flow of air from a ventilator or track, as certain types of microphones are extremely sensitive to such factors.

The microphone should be suspended in an elastic mount, and it is most important to ensure that the cables connecting instrument and microphone not be in sliding or rubbing contact with the body of the aircraft. All tension on the cable must also be avoided. Failure to observe this requirement may result in high parasitic "noise" readings due to vibration and electrical interference. The body of the measuring instrument (noise meter or analyzer) must be provided with shock-absorbers when necessary. It may be found that parasitic "noise" readings due to vibration and interference validate a reduction of at least 10 db in the reading. In taking these measurements it is absolutely essential to compare the instrument readings with a personal evaluation of noise, as it often happens that improper positioning of the microphone near a noisy or vibrating part may substantially distort the results of the test. One listens to the noise to determine whether the microphone is actually picking up the fundamental cabin noise.

2) Secondary noises near the microphone must be eliminated. Thus, in passenger aircraft the individual air vents must be turned off.

In aircraft with pressurized cabins the test must be made with the cabin door closed and the pressure at the level of normal operation. In other aircraft the measurements should be at 1000 m, plus or minus 100. This condition is set only for purposes of standardization, as it is clear that any flight altitude normally used would be just as good.

Amount should be taken of the fact that the results of noise readings in the analyzer or filter bands will vary from one to the next so that the measurement should record the average of at least 3 successive readings at each point. In connection with this, a full round of readings should be made at all the positions of the analyzer frequency switch, and the total f_n level measured, whereupon the entire cycle is then repeated twice more. In measurements may be taken as satisfactory if the range of values for f_n and f_n at each point) does not exceed 1.5 db. To control the consistency of the conditions in which the measurement is made, it is recommended that the total intensity level f_n be measured before and after the measurements with filter or analyzer. In the passenger cabins it is unnecessary to measure at each seat. Measurements at 3 cross section of the compartment, as shown in Figure 3, is adequate.

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Measurements have to be taken on both sides of the passenger compartment, as the noise from the engines is often unequal.

In large aircraft the seats should be at least 75% filled, as sound absorption is much higher under these conditions. In measurements in the crew quarters the microphone must be at the pilot's head.

The β_n spectra values are found from the levels of intensity, $\beta_n f$, in the measurement band, and pertain to the frequency at which the analyzer is set, or the mean frequency of the octave filter, which is determined as $f_{avg} = \sqrt{f_m f_t}$, in which f_m and f_t are the minimum and top frequencies of the filter pass band. With an octave filter, $f_t = 2f_m$, so that $f_{avg} = f_m \sqrt{2}$. Aircraft noise measuring instruments must be light and small, and it is desirable that they have their own power source and be subject to remote control. The range of measurement is from 60 to 130 db. The frequency range in frequency analysis is from 100 to 3,000 c.



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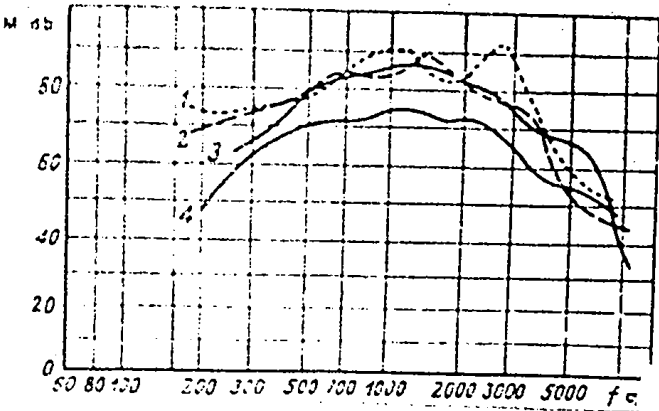


Figure 17. Noise audiogram for several aircraft with reciprocating engines. 1, single-engine aircraft with high noise level; 2, 3, a twin-engine aircraft (different operators); 4, a twin-engine aircraft with low noise level (high-quality headset earphones).

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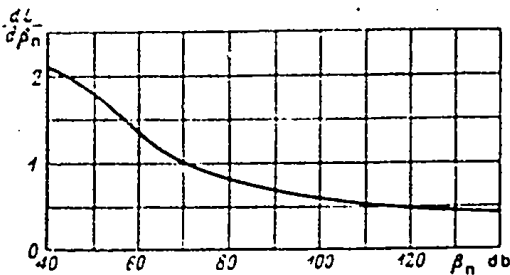
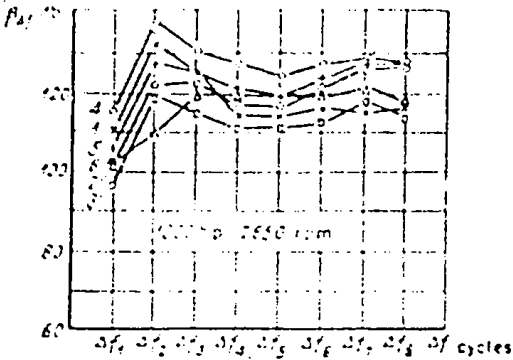


Figure 21. Curve for expression $\frac{dL(\beta_n)}{d\beta_n} = \psi(\beta_n)$.



Δf_1	Δf_2	Δf_3	Δf_4	Δf_5	Δf_6	Δf_7	Δf_8
0.15	0.3	0.6	1.2	2.4	4.8	9.6	19.2

Figure 22. Noise level in octave bands of Δf cycles, in relation to shape of short stack or type of manifold. 1-3, manifold; 4-5, stack.